Coastal Inundation Mapping Guidebook

National Oceanic and Atmospheric Administration
Coastal Services Center

NOAA Coastal Services Center
LINKING PEOPLE, INFORMATION, AND TECHNOLOGY

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Coastal Inundation Guidebook

Introduction

Mapping can be a very important part of understanding inundation issues and preparing for the assessment process. Inundation mapping can be viewed as a four-step process. These steps are detailed in the following document.

Obtain and Prepare Elevation Data

Elevation data (including bathymetry) serve as the base data layer for mapping coastal inundation. Before using elevation data for inundation mapping, it is important to understand requirements and specifications of the data, how to assess the quality of the data, and where to obtain the data. This section answers the following questions:

> What type and quality of data do I need?
> Where can I find elevation data?
> Are the data I have appropriate?
> How do I create an elevation surface?

Prepare Water Levels

To map inundation, a water surface must be generated. That surface can be based on model output or a single value. Different models and approaches to modeling an inundation surface are discussed in this section, which answers the following questions:

> What type of water surface do I want?
> What steps are necessary to prepare water levels?

Map Inundation

With a digital elevation model (DEM) and water level information, geographic information systems (GIS) processes can be used to create layers that represent inundation extent and depth.

> How do I model the water surface?

Visualize Inundation

Visualizing the data is important for assessing exposure and impacts, and serves as a powerful tool for education and awareness. Visualization may range from simple maps to interactive Web viewers.

Obtain and Prepare Elevation Data

What Type and Quality of Data Do I Need?

Before finding or acquiring elevation data, a basic understanding of the types and uses of elevation data is helpful.

Data Needs

The type of information desired from coastal inundation models will largely drive the needs and specifications of the elevation data used. Aspects such as geographic extent, cost, level of detail, magnitude of process, required accuracy, and technical capability will largely determine the appropriate type and quality of elevation data.

Geographic Scale

The coastal manager interested in the effects of seasonal high tides on local road networks has very different elevation needs than an emergency manager trying to prepare for the potential impacts of a large storm. The first may only need elevation for a city or a small part of the county. Working at a smaller geographic scale may have the advantage of using a single data set available from a single source. Working from a single data source generally results in a more consistent product across the area. As the geographic extent expands, the user may need to use elevation data collected at different times, at different resolutions, and at differing accuracy standards. It is important to be aware of the issues and inconsistencies that may arise; larger geographic scale analyses tend to be coarser as well.

Cost

Many elevation data sets are available for use in the coastal zone (see Find Data in this guidebook). This guidebook lists several sites that provide elevation data for free or limited cost. While being free can be considered a good thing, the user must take care to ensure that the data meet their needs. This guidebook, along with the next section (Data Specifications), will help users assess their data.

If data are not readily available for an area, it may be necessary to contract new data collection. The advantage in contracting for data is that data users receive exactly what they want; the disadvantage is that it can be a costly and time-consuming endeavor. To assist with the process of contracting collection of elevation data, the NOAA Coastal Services Center can offer support through its Coastal Geospatial Services Contract.

Level of Detail

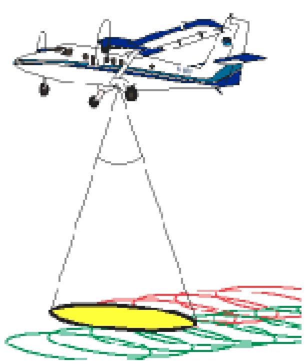
This issue is similar to scale and includes the magnitude of the process being mapped or analyzed. Elevation data needed to model coastal inundation based on a 0.25 meter rise in sea level may be very different from data used to determine inland extent of hurricane floodwaters across a multi-county area. To model a small rise in sea level, a high level of detail and accuracy is needed to accurately determine water extents. For example, small changes in elevation may be significant enough to affect the mapped boundaries of inundation around critical infrastructure. If coarse data are used, this vital information may be incorrect. Conversely, over a large area, less detail may be desirable, since smaller data sets will generally decrease processing time, resulting in receiving critical information much sooner.

Data Types

Elevation data are available in several different forms (points, surfaces, and contours) and can be collected using different sensors and methods. Below is a short description of the more commonly found sources of elevation data.

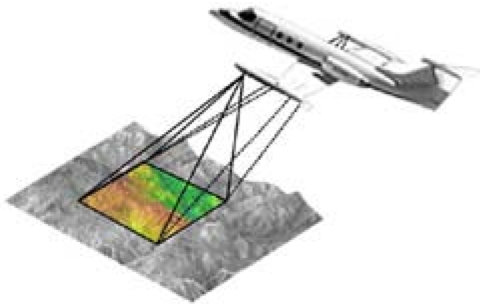
Lidar

Lidar (light detection and ranging) is an active sensor, similar to radar, that transmits laser pulses to a target and records the time it takes for the pulse to return to the sensor receiver. This technology is currently being used for high-resolution topographic mapping by mounting a lidar sensor, integrated with Global Positioning System (GPS) and inertial measurement unit (IMU) technology, to the bottom of aircraft and measuring the pulse return rate to determine surface elevations. Lidar can also be used to collect bathymetry and was actually used to collect bathymetry before being employed to collect topography.



IfSAR

Interferometric Synthetic Aperture Radar (IfSAR or InSAR) is an aircraft-mounted sensor designed to measure surface elevation. IFSAR derives a surface height by correlating two coherent radar images, which are acquired by two antennae separated by a known distance. The radar images are derived from electromagnetic energy returned to each antenna from the first surface it encounters. An interferogram is generated that represents the phase difference of the corresponding pixels of the two radar images. The height of the pixel is calculated from this phase difference and the airborne navigation information.



National Elevation Data Set

The National Elevation Dataset (NED) is a raster product assembled by the U.S. Geological Survey. NED is designed to provide national elevation data in a seamless form with a consistent datum, elevation unit, and projection. NED data sources have a variety of elevation units, horizontal datums, and map projections. In the NED assembly process, the elevation values are converted to decimal meters as a consistent unit of measure, NAD83 is consistently used as the horizontal datum, and all the data are recast in a geographic projection. Older digital elevation models produced by methods that are now obsolete have been filtered during the NED assembly process to minimize artifacts that are commonly found in data produced by these methods. As higher-resolution or higher-quality data become available, the NED is updated bi-monthly to incorporate best-available coverage.

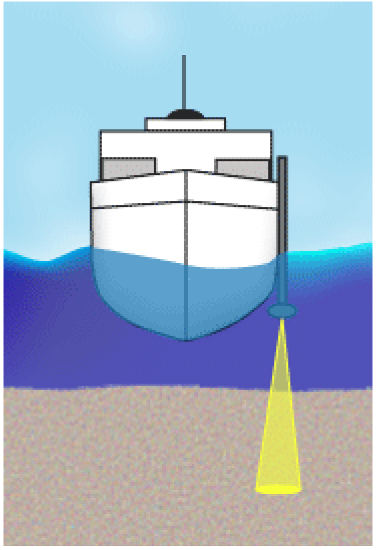
Aerial Image (Photogrammetry)

Stereo aerial imagery is and has commonly been used to generate digital elevation models. The technique can provide very accurate information and is used extensively in highway and road projects. It is less cost effective when working on larger areas and suffers in areas of dense vegetation. Most of the historical data included in the NED were generated using photogrammetry.

Bathymetric

Bathymetric data are considered in this guidebook for the purpose of examining the effects of dropping water levels. The impact of climate change on the Great Lakes is predicted to be a significant drop in lake levels. To understand and visualize the impacts of this lake level drop, bathymetric data are critical to the analysis.

Sonar has active sensors that utilize acoustic energy to collect measurements of seafloor depth and character. Multibeam sensors pulse the bottom with a series of soundings normal to the track of the vessel and record the reflected echoes in an orientation parallel to the vessel track. This produces a swath of data that, depending on specific sensor and mission requirements, is normally several times the water depth. Like other acoustic sensors, multibeam sonar normally collects data in a series of transect lines that allow sufficient sidelap to avoid gaps in coverage. As a rule, the deeper the water, the wider the swath of data collected. Since the swath width is strongly influenced by water depth, some planning of transect spacing is needed to ensure that no gaps occur where water depth decreases.



Where Can I Find Elevation Data?

Find Data

Public domain elevation data are available in a range of extents, accuracy, and formats. The list below represents a sampling of websites providing access to elevation data. While this list may not be all-inclusive, it may be used as a guide for users interested in acquiring elevation data sets for their areas of interest. Those interested in obtaining elevation data are encouraged to also contact their state and local GIS staffs regarding available elevation data.

Digital Coast (NOAA Coastal Services Center)

The NOAA Coastal Services Center's on-line data are provided via Digital Coast. Data are available in several point (.txt, LAS), line (.shp, .dxf), and raster (geotiff, floating point, ASCII grid) formats. www.csc.noaa.gov/lidar/

NOAA Coastal Services Center Topographic and Bathymetric Data Inventory

The Topographic and Bathymetric Data Inventory serves as an index to the best-available elevation data sets by regions. Users can use the interactive viewer to locate and learn about available data sets. www.csc.noaa.gov/topobathy/viewer/index.html

National Elevation Data Set (NED)

NED data are publicly available from the U.S. Geologic Survey (USGS). The data resolution varies by location; the type of data can be reviewed at http://gisdata.usgs.net/website/usgs_gn_ned_dsi/viewer.htm

Center for Lidar Information Coordination and Knowledge (CLICK)

The USGS site CLICK provides access to publicly available lidar point file data sets. The goal of CLICK is to facilitate data access, user coordination, and education about lidar remote sensing for scientific needs. http://lidar.cr.usgs.gov

USGS Topobathy Viewer

The topobathy viewer provides a dynamic on-line map interface that can be used to view U.S. Geological Survey topobathy DEMs. http://edna.usgs.gov/TopoBathy_Viewer/

National Center for Airborne Laser Mapping (NCALM)

NCALM is the National-Science-Foundation-supported Center for Airborne Laser Mapping. The NCALM@Berkeley website provides public access to high-resolution airborne laser mapping data, documentation, and tools to analyze digital elevation data sets. http://calm.geo.berkeley.edu/ncalm/links.html

National Geophysical Data Center (NGDC)

NGDC compiles, archives, and distributes bathymetric data from coastal and open ocean areas, and acts as the long-term archive for NOAA National Ocean Service data collected in support of charting and navigation. www.ngdc.noaa.gov/mgg/bathymetry/relief.html

Laboratory for Coastal Research at International Hurricane Research Center

The International Hurricane Research Center's Laboratory for Coastal Research data were produced as part of the Windstorm Simulation Modeling Project in a contract agreement between Florida International University International Hurricane Research Center (IHRC), Palm Beach County, Broward County, Manatee County, and Miami-Dade County. www.ihrc.fiu.edu/lcr/data/data.htm

LiDARDATA.com

Lidardata.com provides an easy way to see where lidar has already been collected, and to order off-the-shelf archives of the freshest data. www.lidardata.com

North Carolina Floodplain Mapping Program

This website is a free service provided by the State of North Carolina. The latest information on the Floodplain Mapping Program is provided here. www.ncfloodmaps.com

Atlas: The Louisiana Statewide GIS

The objective of this website is to make available to the public data and information related to GIS in Louisiana, GIS data documentation, and data sharing. http://atlas.lsu.edu

Puget Sound Lidar Consortium

The Puget Sound LIDAR Consortium (PSLC) is an informal group of local agency staff and federal research scientists devoted to developing public-domain high-resolution lidar topography and derivative products for the Puget Sound region. http://pugetsoundlidar.ess.washington.edu

USGS Alaska Topobathy DEM

A seamless topographic–bathymetric surface has been created for the area around the coastal town of Seward, Alaska. The digital elevation model (DEM) was developed to study submarine landslides and tsunamis produced by the 1964 earthquake and for generating computer models of tsunami wave propagation and inundation. http://pubs.usgs.gov/ds/374/

Texas Topobathy DEM

This data set is composed of topobathy DEMs that cover the coastal region and continental shelf of Texas. It was sponsored by Texas Sea Grant and the Texas Parks and Wildlife Department, and work was completed by scientists at Texas A&M. ftp://ftp2.tnris.state.tx.us/Elevation/BathyTopo/

Are the Data I Have Appropriate?

Metadata

Before investing significant time and effort in an elevation data set, the user should review the metadata. Simply put, metadata are data about data, representing the who, what, when, where, why, and how of the data. Metadata can answer some of the larger questions about the appropriate use of the data. To learn more about metadata in general, please visit www.fgdc.gov/metadata/.

Accuracy of Elevation Data

The quality of models or depictions of change in water levels or inundation extents is inherently tied to the accuracy of the elevation surface. The most common way to express accuracy is through the root mean square error (RMSE). The RMSE is analogous to the standard deviation of a non-biased data set (i.e., a data set that has errors equally distributed above and below zero), such that about 68% of the data would fall within the range of the RMSE or 1 standard deviation. The other term that is common is $Accuracy_z$. This generally equates to 2 standard deviations (with non-biased data), such that 95% of the data falls within the $Accuracy_z$ value. For example, users can be 95% confident that the elevations in a data set with an $Accuracy_z$ of 25 centimeters will be within ±25 centimeters of the value provided.

In general, increasing accuracy raises the cost of the data; therefore, level of accuracy should be specified based on the needs of the project or likely uses. When considering "likely uses," it is probable that future uses will benefit from higher accuracies, so it is typically better to ask for higher accuracies to increase the shelf life of the data set.

Collected Point Density and Final Cell Size

Elevation data are generally collected at a series of discrete locations (i.e., points) and then interpolated to create a digital elevation model (DEM). The appropriate cell size limits are controlled by the point spacing (point density), such that the resolution and, to a large degree, the accuracy of the resulting elevation surface are directly influenced by this parameter. Increasing point density is, like increasing native point accuracy, a major cost driver. The major advantage of increasing sampling point density is the ability to accurately portray (e.g., increased resolution) elevation. If the points are spaced far apart, important variations in the elevation surface may be missed. As the native point resolution increases, so can the native DEM resolution (e.g., smaller cell sizes) to capture the additional detail.

While there are no hard rules for determining the appropriate DEM cell size from a given point density, as a general rule, the DEM should not have a higher resolution than the data it was generated from (point density). With high density data, it is always possible to down-sample to a smaller data set, but increasing the DEM resolution beyond the point spacing will not provide addition resolution, even though the elevation surface may appear smoother. As cell size increases, the detail generally decreases, but sometimes the trade-off in DEM usability is worth the sacrifice in resolution. Smaller cell sizes allow for finer detail to remain but often at the cost of DEM size (storage) and processing time. The effect of changing the cell size for an elevation data set is demonstrated below (Figure 1); in this case, a DEM technique was chosen to progressively remove artifacts (e.g., trees, houses).

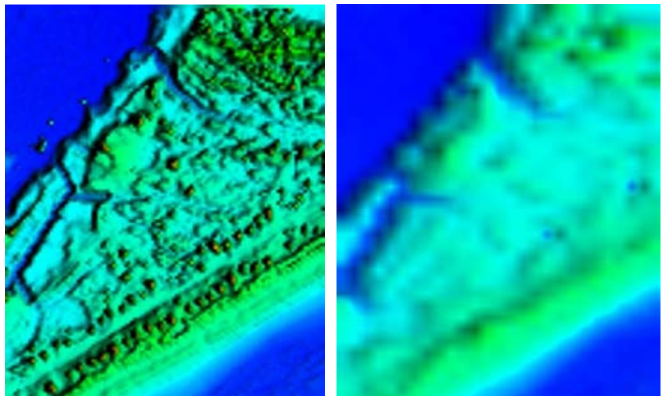


Figure 1. Elevation surfaces created at 5 and 20 meter pixels (left to right)

Return Number (Lidar Only)

Along with higher pulse rates, the ability to discern multiple returns is a major advance in lidar technology (Figure 2) and helps define surface features such as vegetation types. The last return will always be the point used in a bare-earth data set—but bare earth should not be confused with the last return, which may be from buildings, cars, or bridges (Figure 3). When a bare-earth DEM is created, the lidar points are filtered to remove those last return points above the earth's surface

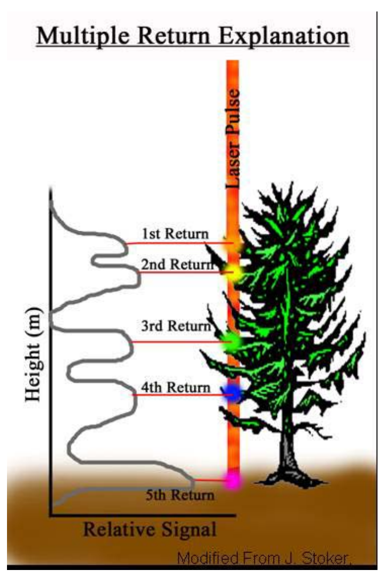


Figure 2. Multiple returns from single laser pulse

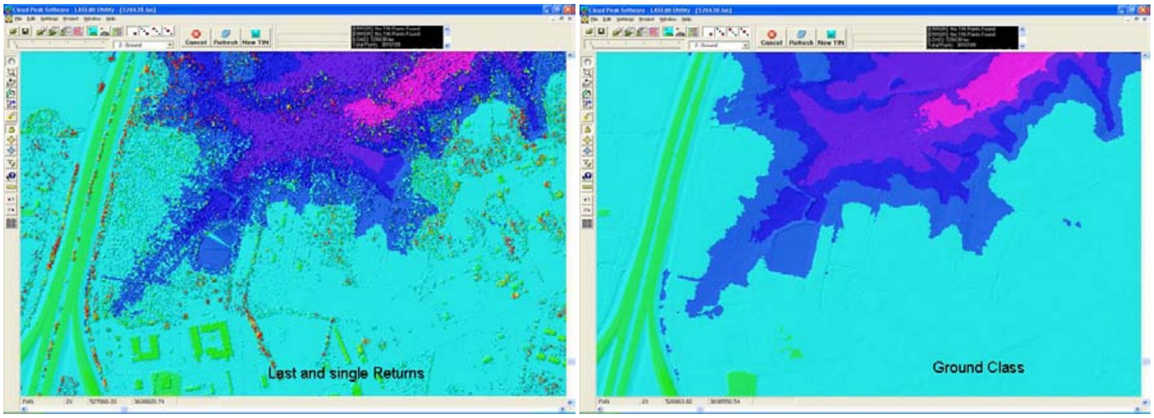


Figure 3. Last return DEM (left) compared to bare-earth DEM (right)

Point Classification (Lidar Only)

Classification of lidar data is usually undertaken to produce a point set that represents only the returns that hit the “bare ground” (Figure 4). The remaining points are typically moved to an “unclassified” class. When creating a DEM, it is then possible to remove all “extraneous” points to create the best possible representation of a bare-earth surface (Figure 4). This represents the simplest classification case; more specification can be accomplished, and classification of features (e.g., trees, houses) is becoming a common trend. The American Society for Photogrammetry and Remote Sensing (ASPRS) classification scheme is used by most lidar producers (Box 1).

Classification Value and Meaning

0 Created, never classified
1 Unclassified
2 Ground
3 Low Vegetation
4 Medium Vegetation
5 High Vegetation
6 Building
7 Low Point (noise)
8 Model Key-point (mass point)
9 Water
10 Reserved for ASPRS Definition
11 Reserved for ASPRS Definition
12 Overlap Points
13-31 Reserved for ASPRS Definition

Box 1. ASPRS classification values

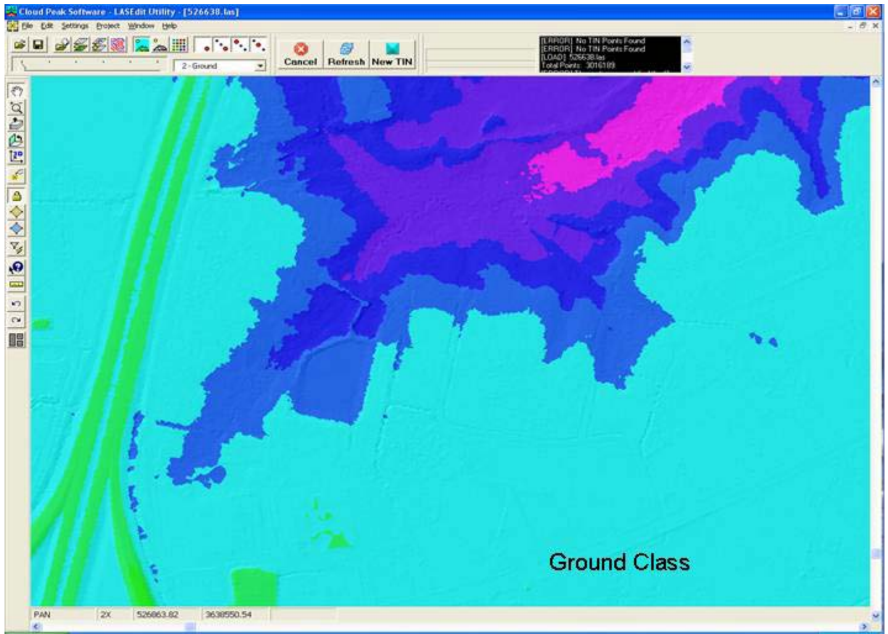


Figure 4. Bare-earth DEM

How Do I Create an Elevation Surface?

DEM Generation

Often, elevation data are only available as point data, and the user will need to create a raster data set for use in modeling and visualization. Software and methods for performing this step are varied and can range from easy and free to complicated and expensive. This section of the guidebook was created to shed light on issues to be aware of during DEM generation.

Software

Tools to handle software and create elevation surfaces range from freeware to costly commercial packages. This section is not designed to review and recommend a software package but to inform the user about features to consider. When selecting a software package, cost will be an important factor. Increased cost often results in increased functionality and analysis power, but a trade-off may be complexity of use. Inexpensive or free software may have fewer sophisticated analysis capabilities but may provide the needed tools in a simple interface.

Surface Generation

Many statistical approaches exist to generate a DEM (surface) from point data; they include nearest neighbor, kriging, binning (min, max, average, most common), inverse distance weighted, and gridding a TIN (triangulated irregular network) surface. Several papers and textbooks discuss these approaches in detail; one suggested resource is *Digital Elevation Model Technologies and Applications: The DEM Users Manual*, 2nd Edition (Maune 2007). The most common are the gridded TIN and inverse distance weighted approaches. Use of the other techniques is valid but may require additional information for a specific use.

As mentioned previously, the cell size selected should be chosen to accurately represent the elevation data while considering the cost and time needed to build and run through inundation models. DEMs are commonly in raster format, largely because this is an efficient format, but they can have other structures or forms as well.

The structure of the DEM grid (structured or unstructured) should also be considered. A structured grid has a uniform grid cell shape—a rectangle—with elevation values at each of the cell's four nodes or at the center of the cell. An unstructured grid (such as a TIN) has grid cells with a triangular shape so that elevation values are at each of the three nodes. Cell size can be highly variable in an unstructured grid and therefore show more detail in areas of a DEM where elevation change may be variable, such as at the shoreline, and less detail in areas of uniform elevation.

Datums

A datum is a reference from which measurements are made. When creating elevation surfaces, special care must be taken to use similar horizontal and vertical datums. Neglecting this step will introduce avoidable error into the final elevation surface. For example, individual terrain (topography and bathymetry) data sets for topobathy surfaces may be referenced to different vertical datums, including orthometric, tidal, and ellipsoidal datums. Each of these datums is best suited for particular applications, such as water flow, navigation, and satellite positioning, respectively. A thorough discussion on resolving datum issues can be found in the NOAA Coastal Services Center's publication, "Topographic and Bathymetric Data Considerations: Datums, Datum Conversion Techniques, and Data Integration."

Review of Elevation Surface

Quantitative Accuracy

The accuracy values are calculated by comparing surveyed ground control points (GCP) to the elevation surface. A TIN surface generated from the lidar elevation data is compared to the GCP point data. A TIN surface is used because there is very little chance that the GCP points will exactly coincide with the lidar elevation data points, and a TIN is a straightforward method for interpolating a value from the nearest points.

In most cases, 20 GCP points are collected per land cover or classification category, and five different land covers or terrain types are chosen. Use of the data for specific applications may depend on the accuracy of the data for specific land covers. For example, shoreline delineation requires only a high level of accuracy in the bare-earth category, whereas flood mapping requires that both bare earth and forested areas have accuracies suitable for creating a specific contour interval. If a data set has a high bare-earth accuracy but was poorly classified for vegetation, then it may not be usable for flood mapping; however, the data set will still work well for shoreline delineation.

For lidar data sets, The American Society for Photogrammetry and Remote Sensing (ASPRS) has published guidelines for analyzing and reporting on lidar's vertical accuracy. The report can be downloaded from www.asprs.org/society/committees/lidar/Downloads/Vertical_Accuracy_Reporting_for_Lidar_Data.pdf.

Qualitative Accuracy

Unlike the clearly defined statistical accuracy requirements, the qualitative aspect of the data is a bit more subjective. While, it does not commonly receive the same amount of attention on the front end, it is a critical check for the successful use of the data. In essence, the accuracy assessment tests only 200 to 300 points in a data set of a billion points, so the qualitative review can be seen as a test of the other billion or so points. There are, however, no specified qualitative accuracy procedures, so familiarity with lidar data in general and the location and intended use in particular are typically necessary. Since it is a "fuzzy" analysis, it is generally best to have it performed by a third party, the purchaser, or a user group.

Some of the most common qualitative "errors" are flightline mismatches (Figure 5), high frequency noise—also called "corn rows" (Figure 6), formatting (Figure 7), misclassification (Figure 8), and data holidays or voids (Figure 9). While many of these problems can be fixed, corn rows are more difficult to remedy. Ultimately, there are no "perfect" data sets, but there is generally a level at which the data lose some of their usability, and that threshold should be considered when specifying the data.

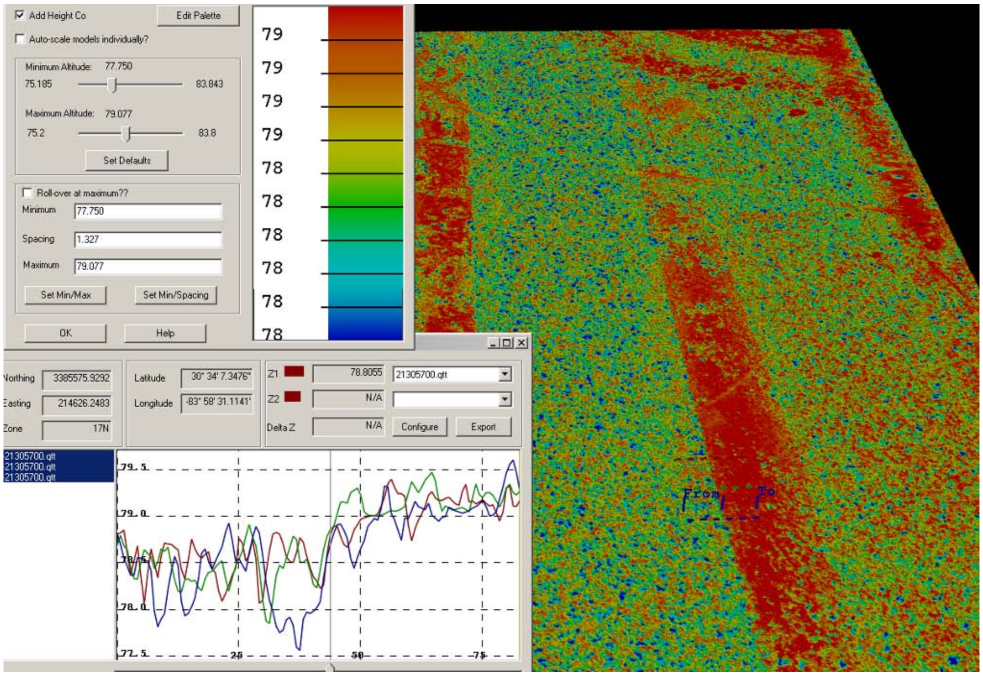


Figure 5. Flightline mismatch evident as linear features

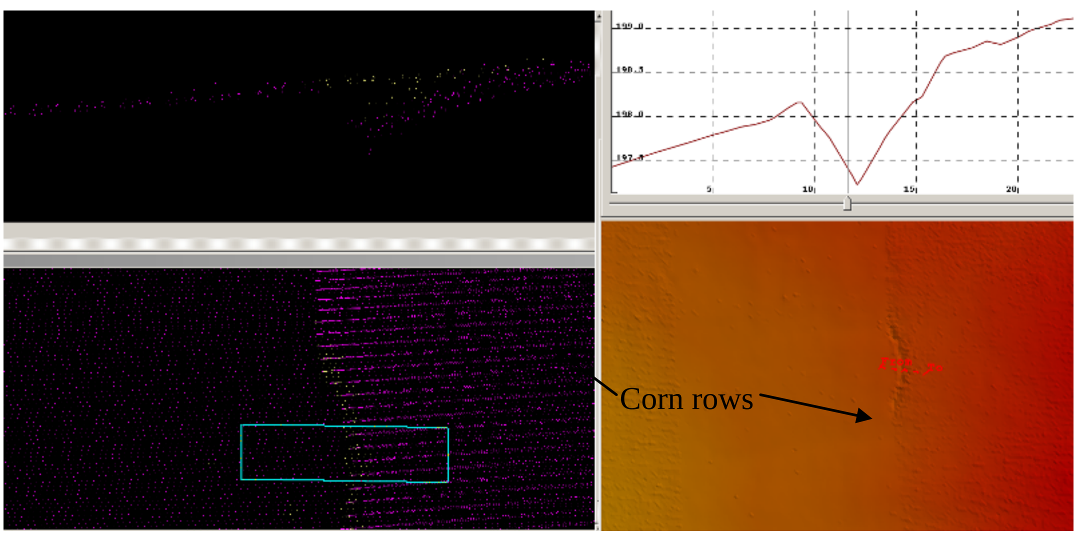


Figure 6. High frequency noise of “corn rows” evident in lidar points

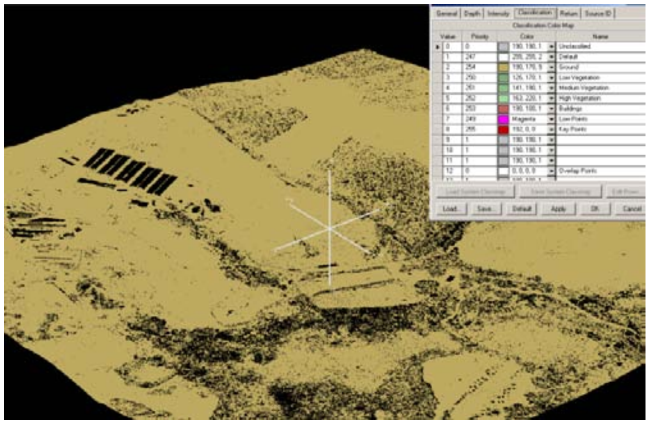


Figure 7. Format issue – only bare-earth points in the lidar file

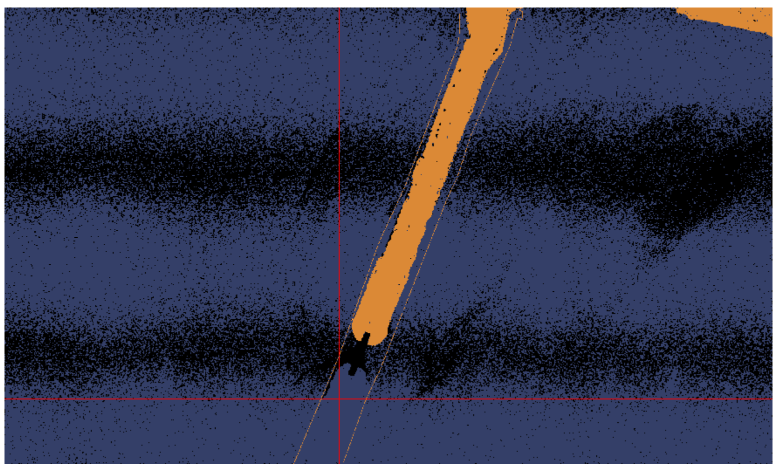


Figure 8. Misclassification of earthen roadway (bottom center in crosshairs) across water body – blue is water, brown is land

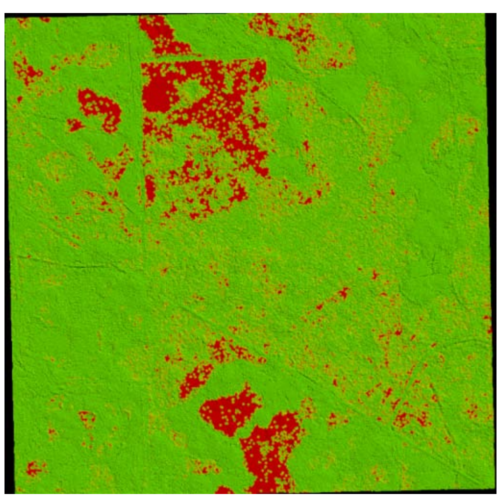


Figure 9. Data "holes" (red = no points) in lidar data.

References:

Maune, D.F., 2007. *Digital Elevation Model Technologies and Applications: The DEM Users Manual*, 2nd Edition. American Society for Photogrammetry and Remote Sensing. Bethesda, MD.

Prepare Water Levels

What Type of Water Surface Do I Want?

Modeled Water Surface versus Single Value Water Surface

In many cases, maps that depict inundation are based on output from a model or combination of models that was used to calculate a water surface. Some prevalent examples of this type of map include the FEMA Flood Insurance Rate Maps (FIRMs) and storm surge zone maps. The FIRMs depict the 1% annual chance flood zone based upon studies that incorporate several different models, such as the Advanced Circulation (ADCIRC) model, Wave Height Analysis for Flood Insurance Studies (WHAFIS), and others. Storm surge zone maps depict the potential extent of storm surge from hurricanes based on model output from the Sea, Lake, and Overland Surges from Hurricanes (SLOSH, ADCIRC, or other models (see "Where Can I Get Water Level Models and Predictions?" below).

Other maps that depict inundation are *not* based on model output representing a water surface. Rather, these maps are based on a single numerical value representing a water level, which is then applied consistently over a study area. Essentially, this method simply "raises the water surface" or delineates a contour based on the selected value. This does not necessarily mean that models were not used, since the selected value may be based on atmospheric, climate, or other empirical models. This approach is most commonly used for mapping sea level rise, and water levels may be based on data published by the Intergovernmental Panel on Climate Change (IPCC) or other studies (see "Where Can I Get Water Level Models and Predictions?" below).

In summary, maps of inundation will generally be based on a modeled water surface or a single value water surface. The guidelines in this section and the following section on mapping provide the steps to prepare water levels and create inundation maps using either approach and for a variety of applications (e.g., sea level rise, storm surge, etc.).

	Modeled Water Surface	**Single Value Water Surface**
Data Readily Available	sometimes	✓
Quickly Create Multiple Scenarios	✗	✓
Accounts for Hydrodynamics of Water Rise	✓	✗

Where Can I Get Water Level Models and Predictions?

Storm Surge Models

- SLOSH

  SLOSH is a computerized model run by the National Hurricane Center to estimate storm surge heights and winds resulting from historical, hypothetical, or predicted hurricanes.

  The SLOSH Display program provides GIS export capability of SLOSH model runs. Contact Arthur.Taylor@noaa.gov to request a copy.

- ADCIRC

  ADCIRC is a system of computer programs for solving time-dependent, free-surface circulation and transport problems in two and three dimensions. These programs utilize the finite element method in space allowing the use of highly flexible, unstructured grids. Typical ADCIRC applications have included modeling tides and wind-driven circulation and analysis of hurricane storm surge and flooding.

  The ADCIRC code system is freely available but is typically run by universities and federal agencies. Therefore, the output may be made available from a variety of sources. The ADCIRC Listserv (adcirc@listserv.unc.edu) is a resource for inquiries.

Sea Level Rise Projections

Cayan, D., M. Tyree, M. Dettinger, H. Hidalgo, T. Das, E. Maurer, P. Bromirski, N. Graham, and R. Flick. 2009. *Climate Change Scenarios and Sea Level Rise Estimates for California 2008 Climate Change Scenarios Assessment.* California Climate Change Center. In preparation.

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Intergovernmental Panel on Climate Change. 2000. *Special Report on Emissions Scenarios.* Cambridge University Press, UK.

Meehl, G. A., T. F. Stocker, W. D. Collins, P. Friedlingstein, A. T. Gaye, J. M. Gregory, A. Kitoh, R. Knutti, J. M. Murphy, A. Noda, S. C. B. Raper, I. G. Watterson, A. J. Weaver, and Z.- C. Zhao. 2007. "Global Climate Projections." In *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change.* S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K. B. Averyt, M. Tignor, and H. L. Miller (eds.). Cambridge, United Kingdom and New York, New York, USA: Cambridge University Press.

Rahmstorf, S., A. Cazenave, J. A. Church, J. E. Hansen, R. F. Keeling, D. E. Parker, and R. C. J. Somerville. 2007. "Recent Climate Observations Compared to Projections." *Science.* Volume 316. Number 5825. Page 709.

Rahmstorf, S. 2007. "A Semi-Empirical Approach to Projecting Future Sea-Level Rise." *Science.* Volume 315. Number 5810. Page 368.

What Steps Are Necessary to Prepare Water Levels?

Approach 1: Single Value Water Surface

1. Select a water level value to depict on a map.

   Select a water level to depict on a map (for example, 1.6 feet or 0.5 meters). For the case of sea level rise, there are published sea level rise (SLR) projections from a variety of sources, including the IPCC and others (see "Where Can I Get Water Level Models and Predictions?"). In some cases, states or local governments have chosen planning targets.

   Regardless of source, be careful to choose a value that is supported by the vertical accuracy of the elevation data. The root mean square error (RMSE) of the elevation data is a useful guide, generally equal to 1 standard deviation (see previous accuracy section) or a confidence interval of about 66%. So, for example, when mapping a 10 centimeter inundation event using elevation data that have an RMSE of 10 centimeters, the mapped area of inundation is, on the whole, about 66% correct. Sixty-six percent confidence means that some areas shown to be inundated should not have been and vice versa. Mapping inundation levels below the RMSE of the data will return lower confidence, and begins to border on a 50-50 chance that it is correct. Mapping an inundation level of twice the RMSE increases the confidence of accuracy at any one location to around 90-95% depending on the surrounding topography.

2. Determine the vertical reference level.

   To meaningfully communicate SLR to local decision makers, in many cases the SLR value is mapped relative to a tidal datum, such as mean high water (MHW) or mean higher high water (MHHW). In this manner, the map will depict the worst daily scenario from high tides.

3. Compute the vertical datum shift.

   The elevation data will be used to "raise the water level" or delineate a contour based on the selected water level. Since most elevation data are based on the North American Vertical Datum of 1988 (NAVD88) orthometric vertical datum, the chosen tidal water level will need to be adjusted to the orthometric datum. This adjustment from the tidal datum (such as MHW or MHHW) to NAVD88 can be done using Vdatum if the transformation grids are available for the area. Alternatively, a local tide gage can provide the conversion factor. Find a tide gage and associated water-level data at http://tidesandcurrents.noaa.gov.

Example:

Prepare water levels to show a 1.6 foot sea level rise on top of MHW for Charleston, South Carolina. The elevation data provided are a DEM referenced to NAVD88.

- Since VDatum is not available for this area, the vertical datum shift will be calculated at the tide gage. Go to the Charleston tide gage at http://tidesandcurrents.noaa.gov/geo.shtml?location=8665530.
- Click on the link for Datums.
- Scroll to the bottom of the page and click on the link for the National Geodetic Survey.
- Use the elevation information provided on the page to calculate the vertical shift between NAVD88 and MHW. See example calculation in the box to the right.

MHW = 5.41 feet

and

NAVD88 = 3.14 feet,

for a difference of 2.27 feet;

So, in order to map MHW on top of NAVD88, a value of 2.27 feet would be used.

Thus, to map 1.6 feet of SLR above MHW, a value of 3.87 (2.27 + 1.6) feet would be used.

Approach 2: Modeled Water Surface

1. Obtain model output: Examples for storm surge inundation include the SLOSH model and the ADCIRC model.

2. Note vertical reference level of model output: Sometimes modeled data are referenced to an orthometric vertical datum that is different than the orthometric vertical datum of the elevation data. If this is the case, then a conversion may be necessary.

3. Compute vertical datum shift: Tools are available to determine the vertical datum conversion values: see Vertcon (www.ngs.noaa.gov/TOOLS/Vertcon/vertcon.html) or VDatum (http://vdatum.noaa.gov).

Map Inundation

How Do I Model the Water Surface?

With the prepared DEM and water level information (model or single value), GIS processes can be used to create data that represent inundation extent and depth.

Approach 1: Single Value Water Surface

1. Use GIS tools (map algebra, conditional statement, or raster calculator) to create inundation depth rasters.
2. Convert depth rasters to polygons representing inundation extent only.

Example:

Using water level information from the previous steps, create inundation polygons and depth rasters showing a 1-foot sea level rise on top of MHW for Charleston, South Carolina.

- Obtain DEM. Note DEM units. If desired, convert units to represent desired final output.
- If desired, remove "No Data" pixels from DEM so they will not be used for inundation calculations.
- Also consider removing pixel values of less than 0 (these might occur offshore or in rivers and waterways). This may or may not create a better final product, depending on the characteristics of the DEM. Often trial and error is a good way to determine the right strategy for a given data set and the desired map or visualization.
- Use the modified DEM and converted water levels from previous steps to create an inundation depth grid. One method is to write a conditional statement. Using the ESRI single output map algebra tool, the conditional statement will resemble the one below.

con (charleston_dem <= 3.27, 3.27 - charleston_dem)

Sets a condition to find all values in the DEM that are less than or equal to 3.27 feet (the SLR value relative to NAVD88)	Where the condition is true, values are subtracted from 3.27 feet to yield water depths. Where false, values are converted to no data.

- Use raster conversion tools to convert the inundation depth raster to a polygon if desired.
- Manual editing may be required to remove “ponds,” or areas that were inundated based on the elevation even though there was no adjacent connection to water or other inundated areas.

Approach 2: Modeled Water Surface

1. Extract points from gridded model output.
2. Create a water surface by interpolating points. Two options for interpolation are inverse distance weighting and kriging.
3. Subtract the DEM from the water surface to create the inundation depth raster.
4. Convert depth rasters to polygons representing inundation extent only.

Example:

Using water level information from the previous section, create inundation polygons and depth rasters showing storm surge inundation from SLOSH model output for Charleston, South Carolina.

An ESRI ArcGIS model is available to automate the following steps for mapping storm surge using SLOSH model output. For more information on how to obtain and use the model, please contact Digital.Coast@noaa.gov

- Project the SLOSH output polygon to match the DEM’s projection.
- Create centroids of the SLOSH output polygon. After some processing, the centroids (or points) will be used to interpolate a water surface representing storm surge.
- Remove dry points. Removing points that are “dry” allows the interpolation to more accurately represent the water surface. “Dry” points represent SLOSH grid cells where no data exist, meaning the model determined that there was no water in that cell.
- Convert SLOSH water level values to meters. This is an optional step and only needed if the DEM’s vertical unit is meters.
- If necessary, use the previously computed vertical datum conversion to convert SLOSH points to the same datum as the DEM.
- Clip SLOSH output points to improve processing. This step reduces processing time by selecting only the points needed to create a water surface that covers the DEM. When creating the clip layer, be sure to make it large enough to include enough “wet” points so that when a surface is created, it covers the entire DEM. This is necessary because the Natural Neighbor interpolation method will only interpolate a surface within the footprint of the input points.
- Interpolate water surface. The Natural Neighbor interpolation method is used to interpolate a water surface from SLOSH output points after the appropriate conversions have been applied.

- Subtract interpolated water surface and DEM to determine inundation. When subtracting the DEM from the interpolated water surface, the resulting values representing inundation will be positive (including zero).
- Process the subtraction result. This step uses a conditional statement to preserve all values representing inundation and nullify all other values. The result is a raster that represents the depth and horizontal extent of inundation. This raster can be converted to a single-value raster or a polygon.

Visualize Inundation

Visualizing the data is important for assessing exposure and impacts, and serves as a powerful tool for education and awareness.

Static Maps
A picture is worth a thousand words. Use GIS to create 2-dimentional maps of inundation.

- Charleston Shallow Coastal Flooding and SLR
- CanVis is a visualization program used to "see" potential impacts from coastal development or sea level rise.

Web Mapping Tools
Internet mapping can allow the user to interact with the data to obtain custom results and maps.

- Coastal Resilience Long Island (partnership with The Nature Conservancy)
- Delaware Sea Level Rise (USGS/NOAA partnership)
- Monash University Sea Level Rise Viewer
- University of Arizona Sea Level Rise Viewer

For further questions about mapping inundation, please contact the NOAA Coastal Services Center at csc.training.geospatial@noaa.gov